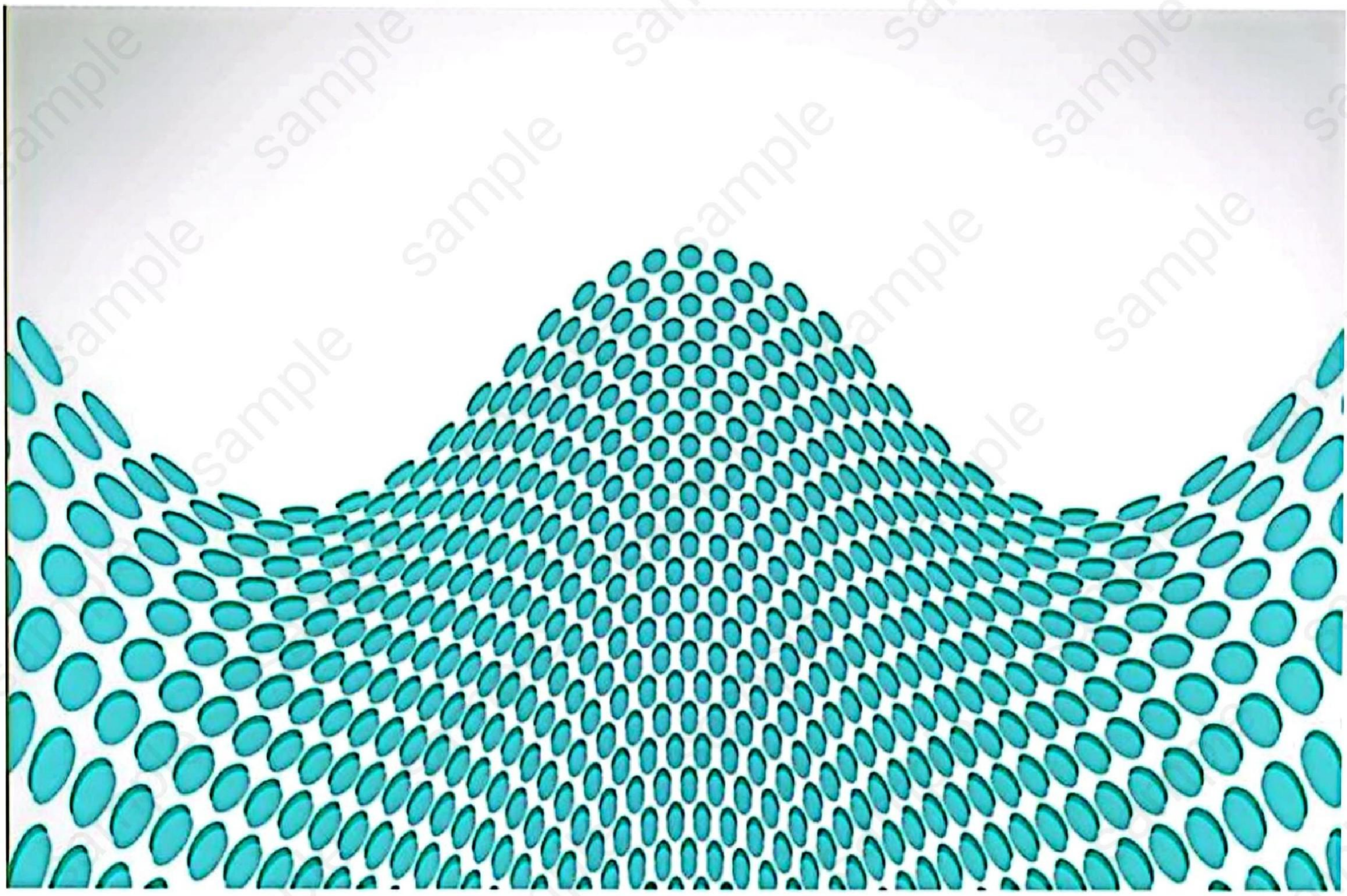

Aouss Gabash

Flexible Optimal Operations of Energy Supply Networks

With Renewable Energy Generation and Battery Storage

SVH Südwestdeutscher Verlag für Hochschulschriften

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Abstract

Due to environmental and fuel cost concerns more and more wind- and solar-based distributed generation (DG) units are embedded in distribution networks (DNs). It is, however, a well-known fact that renewable energy generators are highly fluctuating sources, and therefore, energy storage systems such as battery storage systems (BSSs) are considered as a solution to handle such fluctuations. In general, DG units and/or BSSs convert traditional passive DNs (PDNs) into active DNs (ADNs). Consequently, it is important to investigate the impact and benefits of integrating such entities in conventional DNs.

This dissertation presents a systematic study consisting of modeling, simulation, and optimization of dynamic operations of energy supply networks with embedded renewable generation and storage. Based on complex power flow models, different optimization problems are mathematically formulated and solved.

In this work, novel mathematical models and a new combined problem formulation for active-reactive optimal power flow (A-R-OPF) in PDNs (without DG units and BSSs) and ADNs (with DG units and BSSs) are studied. Typically, DNs consist of two different networks in terms of voltage levels, namely, low-voltage and medium-voltage DNs. For this reason, investigations are carried out separately on both networks. Modeling procedures for PDNs, ADNs, and energy prices are presented. These procedures serve as the basis for this work. Then, simulation studies in PDNs are made to analyze its operating characteristics. In particular, the operation of on-load-tap-changers of main transformers is highlighted. Moreover, an optimization framework is introduced to minimize the total energy losses in PDNs.

In ADNs, two voltage levels with two real case studies are separately considered. On the low-voltage level, a high penetration level of photovoltaic (PV) systems (PVSs) is considered in the network in order to reveal the impact of such a scenario. In particular, the reactive power capability of the inverters of these PVSs is explored. The total revenue from the installed PVSs is maximized whilst the total cost of energy losses and demand is minimized. Using different price models many interesting results are found, e.g., no need to use BSSs in low-voltage DNs for accommodating expected spilled PV energy. On the medium-voltage level, a DN with a high penetration of wind energy and BSSs is considered. In this case, the total revenue from wind parks and BSSs is maximized and the total cost of energy losses is minimized. It is found that a huge reduction in energy losses and reactive energy imports can be achieved. To prolong the life of BSSs only one fixed charge/discharge cycle every day is considered. The solution provides an optimal operation strategy which ensures the feasibility and enhances the revenue significantly. However, due to the fact that the profiles of renewable energy generation, demand and prices vary from day to day a fixed operation of BSSs cannot be optimal.

A flexible battery management system is proposed to adapt to such variations. This is accomplished by optimizing the lengths (hours) of charge and discharge periods of BSSs for each day, leading to a complex mixed-integer nonlinear program (MINLP). An iterative two-stage framework is proposed to address this problem. In the upper stage, the integer variables (i.e., hours of charge and discharge periods) are optimized and delivered to the lower stage. In the lower stage the A-R-OPF problem is solved by a NLP solver and the resulting objective function value is brought to the upper stage for the next iteration. This procedure will converge when number of iterations is reached. Using this flexible system a considerably higher revenue can be achieved.

Zusammenfassung

Bedingt durch Umweltbelange und steigende Kosten für fossile Brennstoffe werden immer mehr Wind- und Solaranlagen (distributed generation, DG) in Verteilernetzen (distribution networks, DNs) installiert. Es ist eine bekannte Tatsache, dass die Einspeisung durch erneuerbare Energieträger starken Schwankungen unterliegt. Ein möglicher Lösungsansatz zur Behandlung dieser Schwankungen ist die Nutzung von Energiespeichersystemen wie z. B. Batteriespeichersysteme (BSS). Der Einsatz solcher Systeme verwandelt traditionelle passive Verteilernetze (PDNs) in aktive Verteilernetze (ADNs). Folglich ist es wichtig, die Auswirkungen und Vorteile der Integration solcher Einheiten in konventionelle Verteilernetze zu untersuchen.

In dieser Dissertation wird eine systematische Untersuchung (bestehend aus Modellierung, Simulation und Optimierung) des dynamischen Betriebs von Energieversorgungsnetzen mit eingebetteten erneuerbaren Energieträgern und Speichersystemen vorgenommen. Basierend auf komplexen Lastflussmodellen werden verschiedene Optimierungsprobleme mathematisch formuliert und gelöst.

In dieser Arbeit werden neue mathematische Modelle und eine neue Problemformulierung für den kombinierten optimalen Lastfluss von Wirk- und Blindleistung (active-reactive optimal power flow, A-R-OPF) in PDNs (ohne DG-Anlagen und BSSs) und ADNs (mit DG-Anlagen und BSSs) vorgestellt. Typischerweise enthalten DNs zwei Spannungsebenen, nämlich Nieder- und Mittelspannung. Deshalb werden Untersuchungen in den beiden Spannungsebenen getrennt durchgeführt. Modellierungsverfahren für PDNs, ADNs und Energiepreise werden vorgestellt. Diese Verfahren dienen als Grundlage der vorliegenden Arbeit. Darauf aufbauend werden

Simulationsstudien in PDNs zur Analyse der Betriebseigenschaften durchgeführt. Insbesondere wird die Auswirkung des Betriebs der Laststufenschalter der Haupttransformatoren hervorgehoben. Darüber hinaus wird ein Optimierungsverfahren zur Minimierung der gesamten Energieverluste in PDNs vorgestellt.

In ADNs werden zwei Spannungsebenen mit jeweils zugehörigen realen Fallstudien getrennt betrachtet. Auf der Niederspannungsebene wird eine hohe Einspeisungsrate von PV-Anlagen (photovoltaic systems, PVSs) angenommen, um die Auswirkungen eines solchen Szenarios zu zeigen. Insbesondere wird die Fähigkeit der Inverter dieser PV-Anlagen zur Erzeugung von Blindleistung untersucht. Die Gesamteinnahmen aus den installierten PV-Anlagen werden maximiert, während gleichzeitig die Gesamtkosten der Energieverluste und die Nachfrage minimiert werden. Durch die Verwendung unterschiedlicher Preismodelle können viele interessante Ergebnisse generiert werden, z. B. besteht keine Notwendigkeit, BSSs in Niederspannungsnetzen für die Aufnahme überschüssiger PV-Energie zu installieren. Auf der Mittelspannungsebene wird ein DN mit einer hohen Einspeisungsrate von Windenergie und BSSs betrachtet. In diesem Fall werden die Gesamteinnahmen der Windparks und BSSs maximiert, während die Gesamtkosten der Energieverluste minimiert werden. Es zeigt sich, dass eine enorme Reduktion der Energieverluste und der Blindleistungsimporte erreicht werden kann. Um die Lebensdauer der BSSs zu verlängern wird nur ein fester Lade-/ Entlade-Zyklus pro Tag betrachtet. Diese Lösung liefert eine optimale Betriebsstrategie, welche die Zulässigkeit gewährleistet und den Profit signifikant erhöht. Aufgrund der Tatsache, dass die Profile der erneuerbaren Energien, der Nachfrage und der Preise von Tag zu Tag variieren, ist ein feststehender Betrieb der BSSs allerdings nicht optimal.

Weiterhin wird ein flexibles Batterie-Management-System zur Behandlung solcher Schwankungen vorgestellt. Dies wird durch die Optimierung der Lade- und Entladezeiten der BSSs für jeden Tag erreicht. Daraus resultiert ein komplexes gemischt-ganzzahliges nichtlineares Optimierungsproblem (mixed-integer nonlinear program, MINLP). Für dessen Lösung wird ein iteratives zweistufiges Verfahren eingeführt. In der oberen Stufe werden die ganzzahligen Variablen (d. h. Lade- und Entladezeiten) optimiert und an die untere Stufe weitergegeben. In der unteren Stufe wird das A-R-OPF Problem mit einem NLP-Löser gelöst und der resultierende Wert der Zielfunktion wird an die obere Stufe für die nächste Iteration weitergegeben. Dieses Verfahren konvergiert, wenn eine Anzahl von Iterationen erreicht ist. Die Verwendung dieses flexiblen Ansatzes resultiert in bedeutend höheren Profiten.

Contents

Appendix A: IEEE-RTS load data

Table A.1: Load data of the low- and medium-voltage DNs (Hourly demand as a percentage of the annual peak demand) [50][7]

Hour	Winter	Spring	Summer	Fall
1	0.4757	0.3969	0.64	0.3717
2	0.4473	0.3906	0.6	0.3658
3	0.426	0.378	0.58	0.354
4	0.4189	0.3654	0.56	0.3422
5	0.4189	0.3717	0.56	0.3481
6	0.426	0.4095	0.58	0.3835
7	0.5254	0.4536	0.64	0.4248
8	0.6106	0.5355	0.76	0.5015
9	0.6745	0.5985	0.87	0.5605
10	0.6816	0.6237	0.95	0.5841
11	0.6816	0.63	0.99	0.59
12	0.6745	0.6237	1	0.5841
13	0.6745	0.5859	0.99	0.5487
14	0.6745	0.5796	1	0.5428
15	0.6603	0.567	1	0.531
16	0.6674	0.5544	0.97	0.5192
17	0.7029	0.567	0.96	0.531
18	0.71	0.5796	0.96	0.5428
19	0.71	0.6048	0.93	0.5664
20	0.6816	0.6174	0.92	0.5782
21	0.6461	0.6048	0.92	0.5664
22	0.5893	0.567	0.93	0.531
23	0.5183	0.504	0.87	0.472
24	0.4473	0.441	0.72	0.413

Appendix B: Data for the low-voltage DN

Table B.1: Data of the low-voltage DN [4]

No. Line	From Bus	To Bus	Length (km)	R_l (ohm/km)	X_l (ohm/km)
1	1	2	0.100	0.195	0.070
2	2	3	0.137	1.900	0.100
3	3	4	0.168	1.900	0.100
4	4	5	0.010	1.900	0.100
5	2	6	0.107	1.900	0.100
6	6	7	0.102	1.900	0.100
7	2	8	0.162	0.868	0.078
8	8	9	0.081	0.383	0.101
9	9	10	0.070	0.868	0.078
10	10	11	0.093	0.868	0.078
11	11	12	0.174	1.117	0.410
12	11	13	0.066	0.868	0.078
13	13	14	0.086	0.868	0.078
14	14	15	0.173	0.868	0.078
15	14	16	0.104	0.195	0.070
16	10	17	0.073	1.117	0.410
17	17	18	0.119	0.519	0.350
18	18	19	0.145	1.117	0.410
19	19	20	0.041	1.900	0.100
20	18	21	0.067	0.519	0.350
21	21	22	0.121	0.519	0.350
22	22	23	0.119	0.519	0.350
23	23	24	0.036	0.868	0.078
24	23	25	0.100	0.868	0.078
25	22	26	0.149	1.117	0.410
26	18	27	0.049	0.519	0.350
27	9	28	0.035	1.900	0.100
28	8	29	0.084	1.900	0.100

Table B.2: Data of the low-voltage DN (Demand daily peak and PFs) [41]

Bus	$P_{peak}(i)$(kW)	PF	Bus	$P_{peak}(i)$(kW)	PF
3	1	0.9	17	5	0.9
4	3	0.9	20	3	0.9
5	16	0.9	25	3	0.9
6	3	0.9	26	3	0.9
7	1	0.9	27	3	0.9
13	3	0.9	29	3	0.9

Table B.3: Data of the low-voltage ADN (Upper bounds of active and reactive power in forward and reverse direction at slack bus) [41]

	$S_{S1.max}$ = 75 kVA			
	$\alpha_{P1.fw}$	$\alpha_{Q1.fw}$	$\alpha_{P1.rev}$	$\alpha_{Q1.rev}$
Value	1	1	0.6	0.6

Table B.4: Data of the low-voltage ADN (PVSs) [41]

Bus	$S_{PCS.max.pv}(i)$ (kVA) = $P_{PV}(i)$ (kW)	Bus	$S_{PCS.max.pv}(i)$ (kVA) = $P_{PV}(i)$ (kW)
3	9	17	9
4	9	20	9
5	9	25	9
6	9	26	9
7	9	27	9
13	9	29	9

Appendix C: Data for the medium-voltage DN

Table C.1: Data of the medium-voltage DN [5]

No. Line	From Bus	To Bus	Length (km)	R_l (ohm/km)	X_l (ohm/km)	B_l (µs/km)
1	1	2	5.7000	0.169111	0.418206	3.9540
2	2	3	1.0100	0.169111	0.418206	3.9540
3	2	4	0.4000	0.169111	0.418206	3.9540
4	4	5	0.3800	0.169111	0.418206	3.9540
5	5	6	0.1300	0.169111	0.418206	3.9540
6	5	7	0.1700	0.169111	0.418206	3.9540
7	7	9	0.2600	0.169111	0.418206	3.9540
8	9	10	0.1400	0.169111	0.418206	3.9540
9	9	11	0.3800	0.169111	0.418206	3.9540
10	11	12	0.5600	0.169111	0.418206	3.9540
11	12	13	0.3000	0.169111	0.418206	3.9540
12	12	14	3.3300	0.169111	0.418206	3.9540
13	14	15	1.0300	0.169111	0.418206	3.9540
14	16	17	1.0800	0.169111	0.418206	3.9540
15	17	18	1.6400	0.169111	0.418206	3.9540
16	18	19	0.4700	0.169111	0.418206	3.9540
17	19	20	0.4700	0.348124	0.468482	3.7571
18	21	22	0.9600	1.391924	0.478811	3.5971
19	19	23	0.1900	0.348124	0.468482	3.7571
20	23	24	1.9400	0.348124	0.468482	3.7571
21	24	25	2.4500	0.348124	0.468482	3.7571
22	24	26	1.6300	0.348124	0.468482	3.7571
23	26	27	1.2000	0.552276	0.485241	3.6035
24	26	28	2.1200	0.348124	0.468482	3.7571
25	28	29	0.7300	0.552276	0.485241	3.6035
26	29	30	0.7500	0.552276	0.485241	3.6035
27	28	31	2.5400	0.348124	0.468482	3.7571
28	23	32	0.3600	0.276519	0.458580	3.8280
29	32	33	0.2600	0.276519	0.458580	3.8280
30	33	34	3.5800	0.552276	0.485241	3.6035
31	33	35	0.7700	0.276519	0.458580	3.8280
32	35	36	2.0800	0.348124	0.468482	3.7571
33	35	37	4.5100	0.276519	0.458580	3.8280
34	37	38	3.2400	0.169111	0.418206	3.9540
35	38	39	0.3000	0.169111	0.418206	3.9540
36	39	40	0.5000	0.169111	0.418206	3.9540

Table C.2: Data of the medium-voltage DN (Demand daily peak and PFs) [40]

Bus	$P_{peak}(i)$	PF	Bus	$P_{peak}(i)$	PF
4	0.641346	0.95	25	0.028975	0.95
6	0.089706	0.87	27	0.015200	0.95
8	0.318725	0.95	30	0.019475	0.95
10	0.057600	0.75	31	0.051775	0.95
13	0.001900	1.00	34	0.020425	0.95
14	0.034675	0.95	36	0.008075	0.95
22	0.004750	0.95	37	0.010450	0.95
23	0.000950	0.95	41	0.216600	0.95

Table C.3: Data of the medium-voltage ADN (Upper bounds of active and reactive power in forward and reverse direction at slack bus) [40]

	$S_{S1.max}$ = 20 MVA			
	$\alpha_{P1.fw}$	$\alpha_{Q1.fw}$	$\alpha_{P1.rev}$	$\alpha_{Q1.rev}$
Value	1	1	0.6	0.6

Table C.4: Data of the medium-voltage ADN (wind turbines, PCSs capabilities and BSSs capacities) [40]

	BSSs stations			Wind-BSSs stations		
Bus	4	9	39	19	28	40
P_W	-	-	-	0.8	0.4	1
$S_{PCS.max.b}$	0.2	0.15	0.1	-	0.05	0.1
E_{BSS}	1.948	1.299	0.455	-	0.844	0.649

Table C.5: Data of the medium-voltage DN (active energy prices for 24-hour-tariff price model in winter and spring) [42]

h	Price ($/MWh)		h	Price ($/MWh)		h	Price ($/MWh)	
	winter	spring		winter	spring		winter	spring
1	55.65	46.43	9	78.91	70.02	17	82.23	66.33
2	52.33	45.70	10	79.47	72.97	18	83.07	67.81
3	49.84	44.22	11	79.47	73.71	19	83.07	70.76
4	49.01	42.75	12	78.91	72.97	20	79.74	72.23
5	49.01	43.48	13	78.91	68.55	21	75.59	70.76
6	49.84	47.91	14	78.91	67.81	22	68.94	66.33
7	61.47	53.07	15	77.25	66.33	23	60.64	58.96
8	71.44	62.65	16	78.08	64.86	24	52.33	51.59

Appendix D: Software implementation of DSI-1

Here is the implementation of the DSI-1 used for carrying out dynamic power flow studies in DNs. The DSI-1 is implemented in the MATLAB-Simulink environment with user-interfaces, as shown in Figs. D.1 and D.2. It is basically a hierarchical model comprising many layers and subsystems.

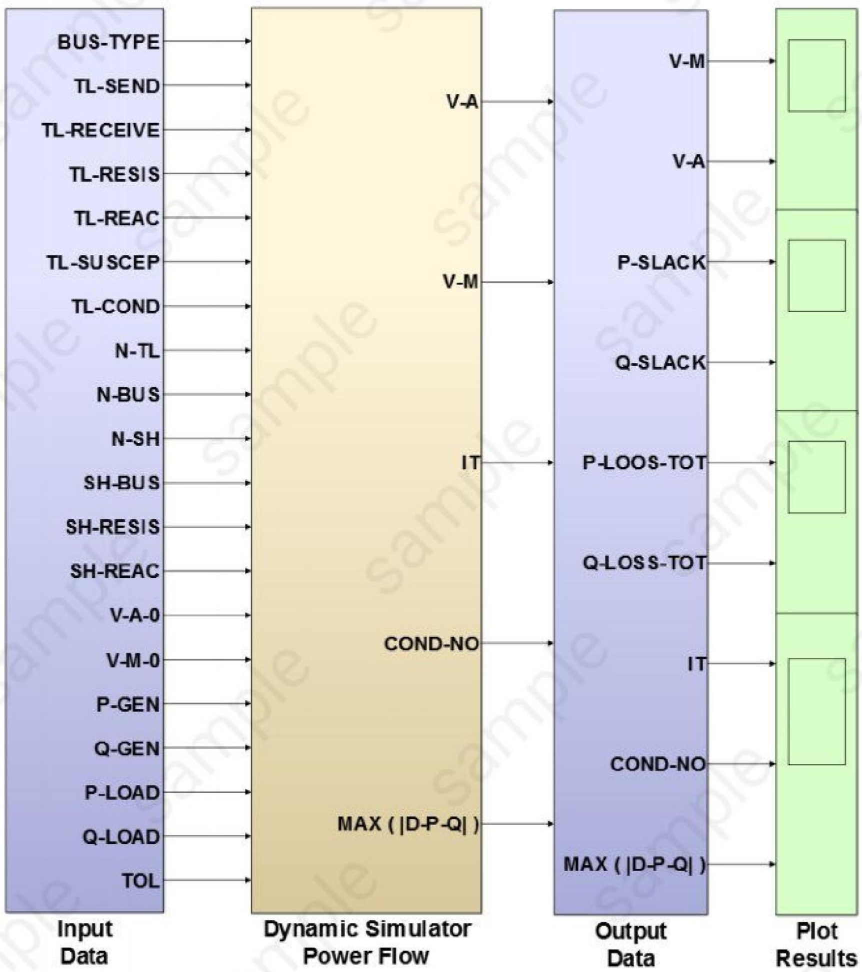

Figure D.1: Main user-interface of the DSI-1 in the MATLAB-Simulink environment.

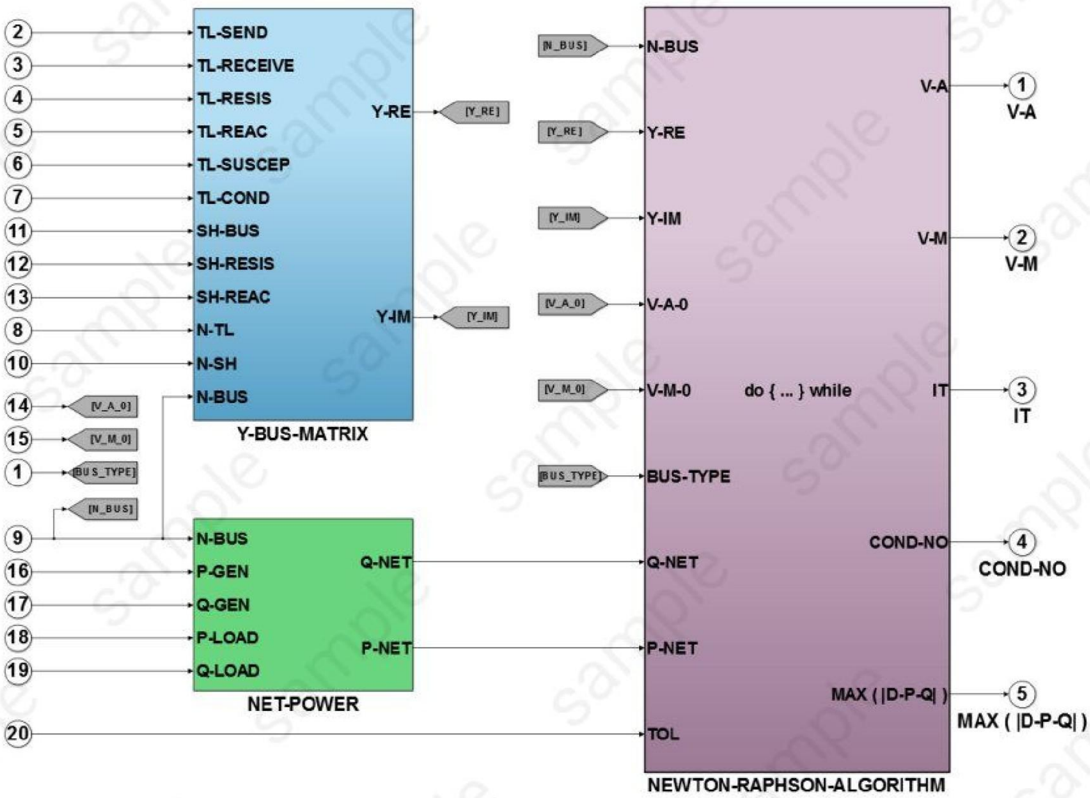

Figure D.2: Schema of the Dynamic Simulator block in Fig. D.1.

Table D.1: Symbols and descriptions of DSI-1 in Figs. D.1 and D.2

Symbol	Description
TL-SEND	Transmission line (send bus)
TL-RECEIVE	Transmission line (receive bus)
TL-RESIS	Transmission line (resistance)
TL-REAC	Transmission line (reactance)
TL-SUSCEP	Transmission line (susceptance)
TL-COND	Transmission line (conductance)
SH-BUS	Shunt elements (number of buses)
SH-RESIS	Shunt elements (resistance)
SH-REAC	Shunt elements (reactance)
N-TL	Number of transmission lines
N-BUS	Number of buses
N-SH	Number of shunt elements
TOL	Tolerance of the calculation
BUS-TYPE	Bus type
IT	Number of iterations
COND-NO	Condition number of the Jacobian-Matrix
D-P-Q	Active-reactive power mismatch
V-M-0	Initial voltage amplitude
V-A-0	Initial voltage angle
V-M	Voltage amplitude
V-A	Voltage angle
P-LOAD	Load active power
Q-LOAD	Load reactive power
P-GEN	Generation active power
Q-GEN	Generation reactive power
Y-RE	Real part of the admittance matrix
Y-IM	Imaginary part of the admittance matrix
P-NET	Scheduled active power
Q-NET	Scheduled reactive power
P-LOOS-TOT	Total active power losses
Q-LOSS-TOT	Total reactive power losses
P-SLACK	Slack active power
Q-SLACK	Slack reactive power

Appendix E: Software implementation of DSI-2

Here is the implementation of the DSI-2 which is a main TR control system. This simulator is implemented in the MATLAB-Simulink environment with a user-interface, as shown in Fig. E.1.

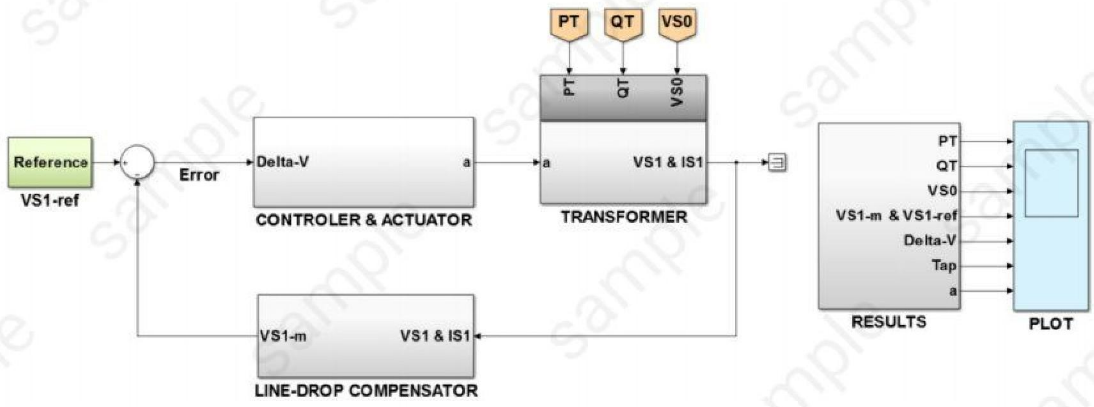

Figure E.1: Main user-interface of the DSI-2 in the MATLAB-Simulink environment.

Table E.1: Symbols and descriptions of DSI-2 in Fig. E.1

Symbol	Description
PT	Transformer active power load
QT	Transformer reactive power load
VS0	Primary transformer voltage
VS1-ref	Reference voltage
VS1	Secondary transformer voltage
IS1	Secondary transformer current
VS1-m	Measuring voltage after line-drop compensator voltage
Delta-V	Voltage error
Tap	Tap position
a	Transformer tap-ratio

Flexible Optimal Operations of Energy Supply Networks

This book presents a systematic study consisting of modeling, simulation, and optimization of dynamic operations of energy supply networks with distributed generation (DG) and battery storage systems (BSSs). Based on complex power flow models, different optimization problems are mathematically formulated and solved. In addition, novel mathematical models and a new combined problem formulation for active-reactive optimal power flow (A-R-OPF) in passive distribution networks (PDNs) (without DG units and BSSs) and active distribution networks (ADNs) (with DG units and BSSs) are studied. Typically, distribution networks (DNs) consist of two different networks in terms of voltage levels, namely, low-voltage and medium-voltage DNs. For this reason, investigations are carried out separately on both networks. Modeling procedures for PDNs, ADNs, and energy prices are presented. These procedures serve as the basis for this work.

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IEEE Member in 2012, received his M. Eng. degree from Aleppo University, Syria, in 2008, and the Ph.D. degree from Ilmenau University of Technology, Germany, in 2013. His research interests include power systems planning, analysis, operation, control, optimization techniques, artificial intelligence, and distributed generation and storage.

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